



Investigation on the formation of microporosity in aluminum alloys



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ABSTRACT

A mathematical model on the microporosity of aluminum castings is proposed, considering the pressure increasing induced by dissolved hydrogen, solidification shrinkage and interface energy. Two types of feeding mode during solidification has been considered, which corresponds to two different microstructures, i.e. columnar dendrite and equiaxed dendrite. For columnar dendritic solidification, Darcy's law was adopted to calculate the pressure drop induced by shrinkage. For equiaxed dendritic solidification, Hagen–Poiseuille equation was adopted before the mass flow stopped. The critical solid fraction f_{sc} was obtained by the mathematical model with the consideration of dissolved hydrogen, SDAS (secondary dendrite arm spacing), grain size and the mass flow passage. The calculation examples are presented and compared with experimental data and other models of former researchers.

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1. Introduction

Porosity in aluminum castings impacts negatively on the mechanical properties, such as ductility, extension strength and fatigue life [1–3]. In many instances the appearance of the porosity is not spherical but follows the dendrites shape, dependent on the gas concentration and the solidification shrinkage. This defect is termed as microporosity and ranges in the size from a few μm to hundreds of μm [3–5].

The present understanding of microporosity formation is that metal flows toward the region where shrinkage occurs until the flow is blocked, either by solid metal or by a solid or gaseous inclusion [1,3,4]. Generally speaking, microporosity in alloys is resulted from the incomplete feeding in the mushy zone, i.e. the volume shrinkage associated with solidification cannot be compensated by the interdendritic liquid flowing opposite to the displacement of the isotherms. This flow induces a pressure drop in the interdendritic liquid. Meanwhile, temperature decreases during solidification will reduce the solubility of gases, such as hydrogen, but the real concentration of the gas in the liquid increase due to segregation. Once the gas concentration in the interdendritic liquid exceeds the solubility limit, pores will form [2–8].

The pressure drop induced by solidification shrinkage of aluminum alloys can be classified into two different situations, i.e.

columnar dendritic solidification and equiaxed dendritic solidification. These two types were treated in accordance with the interdendritic feeding mode in more recently calculations [5–9] and were described by Darcy's equation indistinguishably. Darcy's equation is suitable for the condition that the alloys solidified with columnar dendritic microstructure, with typical dendrite arm spacing, where the liquid flow can be treated as a flow through a fine porous media. Darcy's law can be applied to estimate flowing velocity and the pressure drop in the channels [7–9]. In the case of equiaxed dendrite solidification, mushy zone is denned as a liquid with suspended solid particles when solidification starts. Hagen–Poiseuille equation can be used for equiaxed dendritic solidification until mixed mass stopped flowing [3]. Once the solid grains start to interact with each other and the material develops certain strength, large scale feeding will completely stop, below a certain temperature.

Upon these discussions, a mathematic model to investigate the conditions of microporosity formation was developed. The model considered the effects of the concentration of dissolved hydrogen, SDAS, grain size and the parameters of mass flow passage.

2. Physical model for the formation of microporosity

Recent solidification models [4,5,7,8] assumed that when a gas pore appears in the mushy zone in the last stage of solidification, after dendrite coherency, it was entrapped in the dendritic network. If the metal flow toward the mushy zone was blocked, the pore became the starting point of microporosity. Mathematically, this can be expressed through a pressure balance equation stating

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that the pressure exerted by gas dissolution, P_G , must be equal to the sum of the local pressure in the mushy zone, P_{mush} , and the pressure applied by the surface energy on the pore, P_r . It was assumed that a gas pore is stable provided that the supersaturation, or the excess pressure, in the gas is sufficiently high to overcome the surface energy. This balance is expressed as

$$P_G = P_{mush} + P_r \quad (1)$$

$$P_{mush} = P_{appl} + P_{st} - P_{shr} \quad (2)$$

where P_G is the pressure of the gas dissolution, P_r is the pressure applied by the surface energy inside the pore with the radius r , P_{appl} is the pressure applied on the melt surface and equals to atmospheric pressure, P_{st} is the metallographic pressure and P_{shr} is the pressure drop due to the resistance of the dendrites to the interdendritic melt flow and solidification shrinkage in mushy zone.

Microporosity nucleation can take place when the gas dissolved in the liquid exceeds its maximum solubility. The stability of such a pore is controlled by the surface energy pressure on the gas pore, P_r , given by,

$$P_r = 2\gamma_{LG}/r \quad (3)$$

where γ_{LG} is the liquid surface energy; r is the principal radius of the gas pore.

Eqs. (1) and (2) can be rearranged to highlight the criterion of microporosity formation, i.e.

$$P_G > P_{appl} + P_{st} - P_{shr} + P_r \quad (4)$$

This equation shows that the driving forces for pore formation are the gas and shrinkage pressure, and the resistances are P_{appl} , P_{st} and P_r .

2.1. The pressure of dissolved hydrogen in liquid phase

It is necessary to consider only hydrogen as a sole contributor to the microporosity because it is the only gas with a measurable solubility in aluminum alloys. In general, microporosity increases with the concentration of hydrogen dissolved in the melt. Thermodynamic principle for the pressure of dissolved hydrogen in liquid should be first discussed.

The pressure of hydrogen in atmosphere P_G can be calculated based on the reaction $\frac{1}{2}\text{H}_2(\text{g}) = [\text{H}]$,

$$P_{\text{H}_2}^{1/2} = C_{\text{H}}^L/K_L \quad (5)$$

where C_{H}^L is the concentration of hydrogen dissolved in the liquid, P_{H_2} is the pressure of $\text{H}_2(\text{g})$ inside the pores, and K_L is equilibrium constant of gas dissolution reaction in liquid. The value of K_L is 0.6 cc/100 g atm^{1/2} [5].

Hydrogen can dissolve and diffuse in aluminum alloys, with the diffusivity much larger than that of other alloying elements. When the diffusion of hydrogen are sufficient both in the solid and liquid, the liquid composition during solidification is given by,

$$C_{\text{H}}^L = C_{\text{H}}^0/[f_L + (1 - f_L)k_{\text{H}}] \quad (6)$$

To deal with the partitioning of hydrogen between the solid and liquid phases during solidification, the equilibrium partition ratio for dissolved hydrogen is needed. The data for dissolved H in the pure aluminum will be obtained according to,

$$\log_{10}k_{\text{H}} = \log_{10}(C_{\text{H}}^S/C_{\text{H}}^L) = 181/T - 1.369 \quad (7a)$$

$$k_{\text{H}} = C_{\text{H}}^S/C_{\text{H}}^L = \exp(417/T - 3.15) \quad (7b)$$

where C_{H}^S and C_{H}^L are the concentrations of hydrogen in the solid and liquid phases, respectively, k_{H} is the extrapolated value of the equilibrium partition ratio of hydrogen in aluminum at temperatures

lower than melting point. According to Eq. (7), k_{H} varies somewhat in the solidification temperature range of aluminum alloys and the average value of 0.069 is used for the calculation [5].

Combining Eqs. (5)–(7), the pressure of dissolved hydrogen in liquid can be expressed by,

$$P_G = \frac{C_{\text{H}}^{02}}{K_L^2[f_L + (1 - f_L)k_{\text{H}}]^2} \quad (8a)$$

or

$$P_G = \frac{C_{\text{H}}^{02}}{K_L^2[1 - f_S + k_{\text{H}}f_S]^2} \quad (8b)$$

2.2. Radius of microporosity

The measurements of pore growth in the pure aluminum revealed that, the pore was controlled by the hydrogen diffusion through the liquid phase when it was far away from the SL interface. A sudden increase of the pore growth rate occurs when the solute field ahead of the SL interface overlaps with the pore. If the interface is non-planar, the pore will be entrapped by the solid. The size of the pores may be of the order of micrometers to millimeters [3–5,7].

For columnar dendritic solidification, experimental results [10–16] supported that the spacing between the secondary dendrite arms is the proper position for the micro-pores to nucleate. In many instances the appearance of the pore is not spherical but follows the dendrites shape. The radius of microporosity r can be predicted by,

$$P_r = \frac{2\gamma_{LG}}{r} = \frac{4\gamma_{LG}}{\lambda_2} \quad (9)$$

where λ_2 is the secondary dendrite arm spacing.

For equiaxed solidification, similar to the cross section of columnar dendritic microstructures, the grains may have an interlocking type of arrangement rather than a square type of arrangement, and the interdendritic space is a groove of width θ [4] described in Fig. 1,

$$\theta \approx f_L d_1/2 \quad (10a)$$

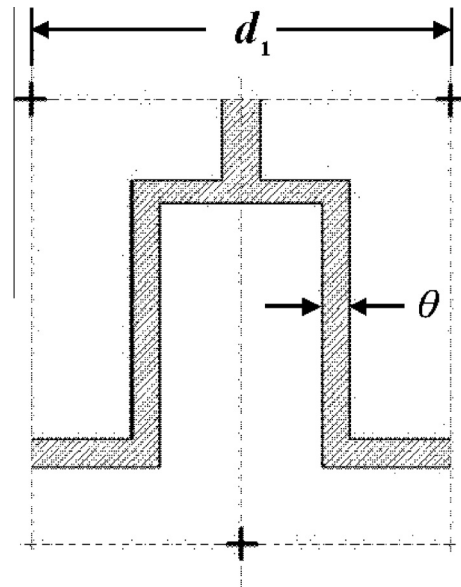


Fig. 1. Interlocking arrangement of equiaxed grains and dendritic grooves among three grains.

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